

GIPSY-OASIS II: A HIGH PRECISION GPS DATA PROCESSING SYSTEM AND GENERAL SATELLITE ORBIT ANALYSIS TOOL

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ABSTRACT

The GIPSY-OASIS II (GOA II) is an advanced software system used for analysis of tracking data from Earth-orbiting satellites. It has special modeling and estimation capabilities for the Global Positioning System (GPS). GOA II was developed by the Jet Propulsion Laboratory with NASA funding and is in widespread use around the world as a modern, big, precision, versatile and efficient tool for orbit determination with capability for unattended, automated operations. GOA II also offers many powerful and unique simulation and covariance analysis capabilities used in system design and tracking accuracy assessment. The software has been used in analysis of tracking data from low-Earth altitude (500 km) to geosynchronous altitude (36,000 km) and has a demonstrated capability for 2-cm orbit accuracy in low-Earth orbit. It handles multi-station, multi-satellite data as well as satellite-satellite tracking scenarios. For GPS satellites, orbit accuracies of 10-30 cm are routinely obtained in automated, daily data processing. Recent geosynchronous tracking analyses have demonstrated 10-25 m orbit accuracy. The software is easily ported to small UNIX workstations. GOA II recently received an award for excellence from NASA under the Space Act and is currently licensed to users through the California Institute of Technology.

1. INTRODUCTION

GIPSY-OASIS II (GOA II) is a general satellite tracking and orbit determination software system which includes many special features tailored to Global Positioning System applications. GOA II has evolved from two earlier versions, OASIS (Orbit Analysis and Simulation Software) and GIPSY (GPS Inferred Positioning System). Several different NASA programs have jointly contributed to the development of GOA II, including the geodynamics program; the Topex/Poseidon mission; and NASA's Deep Space Network (DSN) which is operated by the Jet Propulsion Laboratory (JPL). Due in part to the diverse interests of the sponsors of the software, it has a myriad of capabilities and can be used for (or easily adapted to) most any Earth orbiting tracking problem. The current version of the software system includes more than 380,000 lines of code, plus 160,000 lines of comments. Key features of GIPSY-OASIS II include the following:

- It is capable of multi-station, multi-satellite, and satellite-satellite processing. The number of stations and satellites handled simultaneously is limited only by the memory of the computer.
- It utilizes the latest and the most accurate models for satellite dynamics and radio metric measurements including the T20 solar pressure model for GPS satellites, the new GPS yaw attitude model, user-selectable gravity fields, atmospheric drag, and empirical forces.
- It allows the estimation of any user-defined subset of parameters and has a flexible first-order Markov process-noise parameterization capability for any designated estimated parameters, including satellite position and velocity. The update time, the time correlation and the steady-state sigma can be varied as desired. Through white-noise modeling of transmitter and receiver clocks, GOA II provides optimal single and double differencing of measurements.

- It incorporates a stable, high precision Square-Root Information Filter (SRIF) for sequential estimation of parameters and a U-D factorized smoothing algorithm.
- A highly modular design simplifies continuing improvements and enhancements.
- It is fully compatible with small UNIX computer systems and is highly portable. GOA II is currently running on HP, Sun, and IBM RS6000 workstations. Processing is automated using UNIX utilities `esh`, `perl`, `awk`, and `sed`.
- It has a comprehensive on-line user's guide for all modules directly interfaced with the users.
- GOA II is copyrighted and licensed through the California Institute of Technology. Hundreds of users worldwide currently use GOA II for a wide variety of satellite tracking and positioning applications. JPL offers a training course which can be tailored. GOA II will be a primary analysis tool for GPS geodetic arrays in the U.S. and Japan (Geographical Survey Institute GPS Network) for seismic monitoring.

GPSY-OASIS II has been used successfully in the following applications:

- As an analysis center for the International GPS Geodynamics Service (IGS), JPL uses GOA II to automatically process on a daily basis worldwide GPS data to routinely provide 20-cm accurate GPS orbits, 1-cm accuracy for ground positions worldwide, 1-cm accuracy for the Earth's pole position, and 0.03 msec (-1.5 cm) accuracy for change in Earth rotation.
- Daily GPS data from the low-Earth oceanographic Topex/Poseidon satellite and from ground stations are analyzed in an automated GOA II data processor at JPL. Quick-look automated solutions for the Topex orbit available the next day are accurate to 5 cm (radial). The most accurate post-fit solutions from GOA II show 2-cm radial orbit accuracy for Topex/Poseidon.
- GPS data acquired from the low-Earth Extreme Ultraviolet Explorer (EUVE) satellite have been analyzed to demonstrate m-level orbit determination accuracy after the fact, with 15-m accuracy demonstrated for data analysis in a real-time mode. Sub-meter 3D real-time knowledge of the Topex orbit is typically available from automated GOA II processing.
- High accuracy (10-30 cm) solutions for low-Earth orbiters (SPOT2 and Topex/Poseidon) have also been obtained with GOA II processing *non-GPS* range and Doppler data.
- Recent GOA II analysis of GPS data from the low-Earth MicroLab satellite has resulted in decimeter-level orbits used to produce 1-deg accurate atmospheric temperature profiles.
- Tracking data from geosynchronous satellites have been analyzed using GOA II. JPL recently demonstrated 10-m precision for INMARSAT orbits, and also completed an experiment for ground-based TDRS tracking using a unique tracking technique in which 20-meter accuracy was attained. GOA II has also processed data from an Air Force (DSP) GEO.
- A wide spectrum of simulation and covariance analyses have been performed for the design and accuracy assessment of various orbit tracking systems, with and without including GPS satellites. Recent and ongoing studies have included various commercial low-Earth satellites; military low-Earth, high-Earth, and geostationary satellites; and more than a dozen NASA missions involving satellites ranging from very low to above geosynchronous altitude.

II. GPSY-OASIS II OVERVIEW

The overall structure and flow of execution for GOA II is shown in Fig. 1. The software was designed and written as a general purpose satellite tracking analysis system. To maximize flexibility the design was made highly modular. There are about a dozen key modules and sub-modules that may be called in sequence (or a sub-sequence may be iterated) in the course of an

estimation run. There is no "hard-wiring" of the modules one to another. Rather, their operation is governed by a higher-level executive consisting of UNIX shell scripts which effectively take the place of the analyst for routine or automated operations. For unique or non-standard applications, an analyst may choose to execute the modules individually. Simple automatic execution of the full system, from data retrieval to estimation and archiving of a full suite of orbit, clock, and geophysical parameters, requires only a few pages of UNIX script. However, robust, foolproof execution for operational delivery of time-critical or mission-critical parameters, as is currently done for NASA's Topex/Poseidon mission and for the International GPS Service, may require several thousands of lines of UNIX script. These more elaborate executives perform "everything from intelligent memory and file management to exhaustive verification and correction of the computed products; in effect, they embody the knowledge and automate the decision processes of an expert analyst to assure a fault-free product.

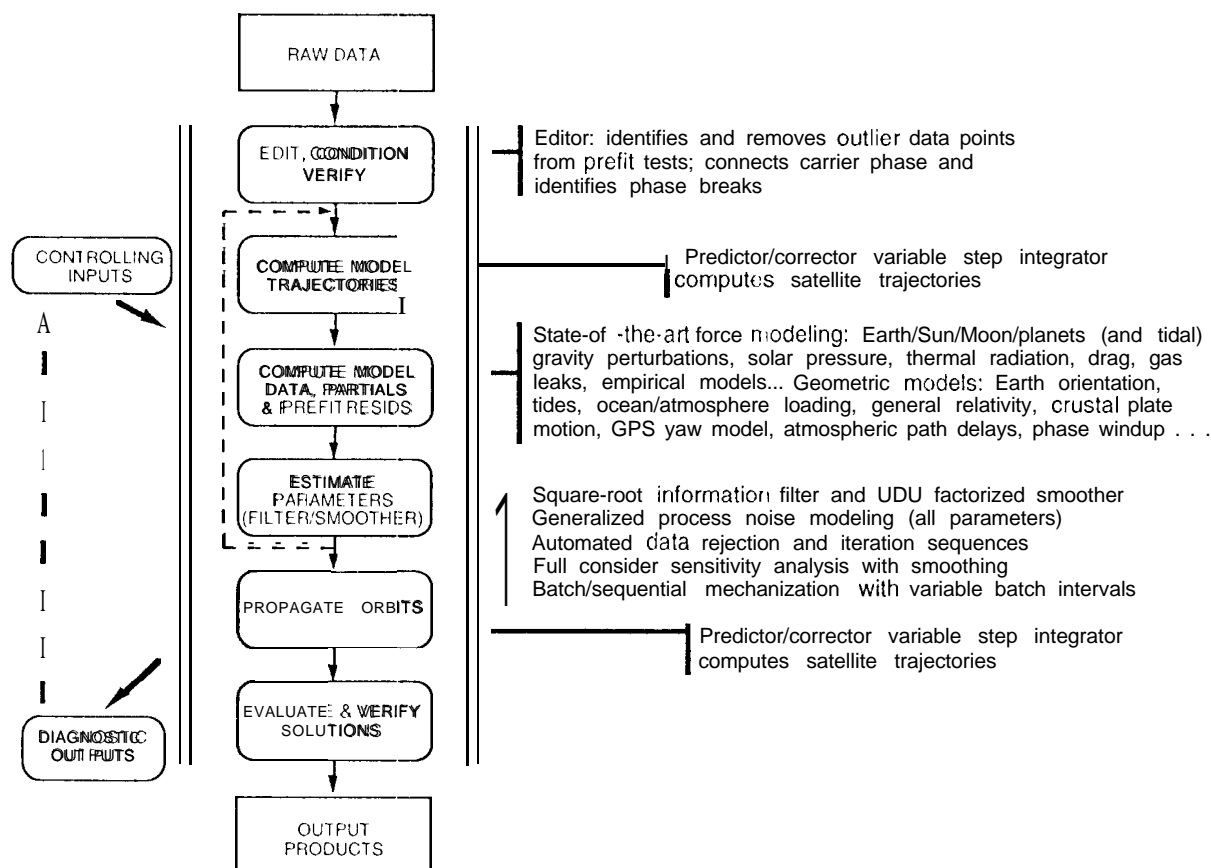


Fig. 1. Flow diagram for GIPSY-OASIS 11. Data can be GPS and/or non-GPS: carrier phase; Doppler; range; pseudorange; one-, two-, and three-way datatypes; angle data; and position and velocity dots. Typical output products estimated can include: past, current, and future satellite ephemerides; ground coordinates; atmospheric delays; biases; timing offsets.

One virtue of this architecture is that GOA 11 can be optimized to an usually wide range of satellite orbit estimation problems simply by modifying (or creating) a relatively small amount of UNIX script. Usually the GOA 11 code itself which has been tuned for numerical stability, precision, and computational efficiency over many years of demanding USC, need not be touched at all.

A substantial amount of effort has been expended to provide advanced and sophisticated analysis and processing capabilities in GOA II for GPS applications. As installed at JPL, GOA II can be run in a highly automated mode outlined sequentially in Fig. 1. Different criteria can be used for

determining when to start processing data, but the quantity of data as well as the geographic distribution of the sites from which data have been received are typically taken into account by the autonomous processor, which intelligently decides when the data received are enough to meet the specific mission requirement. The data retrieval process itself is also automated, with data arriving through modems, high speed lines, or satellite links, all controlled autonomously without human intervention. In this mode, analysts are ordinarily only needed to perform spot checks on the continuous operation of the software. A series of procedures or scripts enable analysts to proceed through many steps of complicated analysis by entering a single one-word command. The processing can be made to repeat day after day or over a specified interval. The system runs unattended for days on small UNIX workstations processing over 100,000 measurements/day from dozens of sites located around the globe, estimating more than 25,000 parameters/day, and providing the most accurate ground and space measurements possible with the GPS system. The use of GOA II in and of itself has lowered the cost of doing daily operational GPS processing for the Topex/Poseidon oceanography by about a factor of five (from 5 to 1 workyear/yr).

Unique and special features

Data Editor

Raw measurements are formatted, edited, conditioned, and verified. For range or pseudorange measurements, such editing may be as simple as detecting outliers. For carrier phase data (continuously counted, or integrated Doppler), cycle slips must be detected and either repaired or accounted for in the model and in the filtering strategy. The software modules, while they are distinct programs, are also fully integrated so that the cycle breaks detected in the editor program are automatically handled properly later on in the filter module. The CJPS data editor has a number of special features to enable rapid and accurate editing of very large amounts of data. It recognizes data from a variety of commonly used commercial GPS ground receivers as well as from GPS space receivers and makes adjustments for subtle effects such as differences in definition of time tag. The GPS data editor optimally treats the GPS data whether it has both L1 and L2 code observables, or L1 code-free, or L1/L2 code-free observable. GOA II also has several modules which can pre-analyze data from a global or regional network and identify and correct or eliminate questionable data by performing rapid point position individual or differential (in station pairs) solutions. In addition to these multiple layers of data quality control, the filter/smoothener has an automated feature which can remove questionable measurements individually and iterate through the grand solution without reprocessing the entire data set over again.

Orbit Integrator

The orbit integrator propagates orbits of satellites in time and computes transition matrices for dynamic parameters. It is used both to construct an a priori model for the spacecraft orbits and in the later refinement and estimation of precise ephemerides. The a priori model is important because in many cases, satellite orbit determination is a non-linear problem. The integrator itself also plays a crucial role in the orbit fitting process itself since it provides the dynamic parameter partials and transition matrices. The basic equation governing the motion of a satellite relates the position $[\mathbf{r}(t)]$, velocity $[\dot{\mathbf{r}}(t)]$, and acceleration $[\ddot{\mathbf{r}}(t)]$ over time:

$$\ddot{\mathbf{r}} = \mathbf{f}(\mathbf{r}, \dot{\mathbf{r}}, \mathbf{p}, t) \quad (1)$$

$$\mathbf{f} = \mathbf{f}_{\text{point mass}} - t \mathbf{f}_{\text{oblateness}} - t \mathbf{f}_{\text{solar pressure}} + \dots$$

where \mathbf{f} describes the external accelerations on the satellite as a function of the Spacecraft state (position and velocity, \mathbf{r} and $\dot{\mathbf{r}}$), a set of constant parameters (\mathbf{p}), and time (t). The orbit integrator computes a unique solution to these equations given the set of parameters \mathbf{p} , the force models, and initial conditions $[\mathbf{r}(0)$ and $\dot{\mathbf{r}}(0)]$. The evaluation of the first and second integrals of the equation of motion [eq. (1)] above in this process is what gives rise to the term "orbit integrator." Also

integrated are the variational equations, which describe the sensitivity of the satellite state and its time derivatives to the initial conditions and the parameters, p . The numerical integration scheme is a variable order Adams-Bashforth-Corridor with a unique ability for direct integration of second order equations [1]. The orbit integrator module was designed to be both flexible and user friendly. It is namelist-driven and although there are more than 150 namelist items, they have self-explanatory names and most of them are conveniently defaulted. Optional inputs include: activation of a large number of force models with control over their parameters; selection of various coordinate frames for input/output; and custom-design of arbitrary spacecraft. The software is accompanied by a host of utilities to read and analyze its products. The force models are coded so that they may be switched on or off, or combined differently through user input namelists.

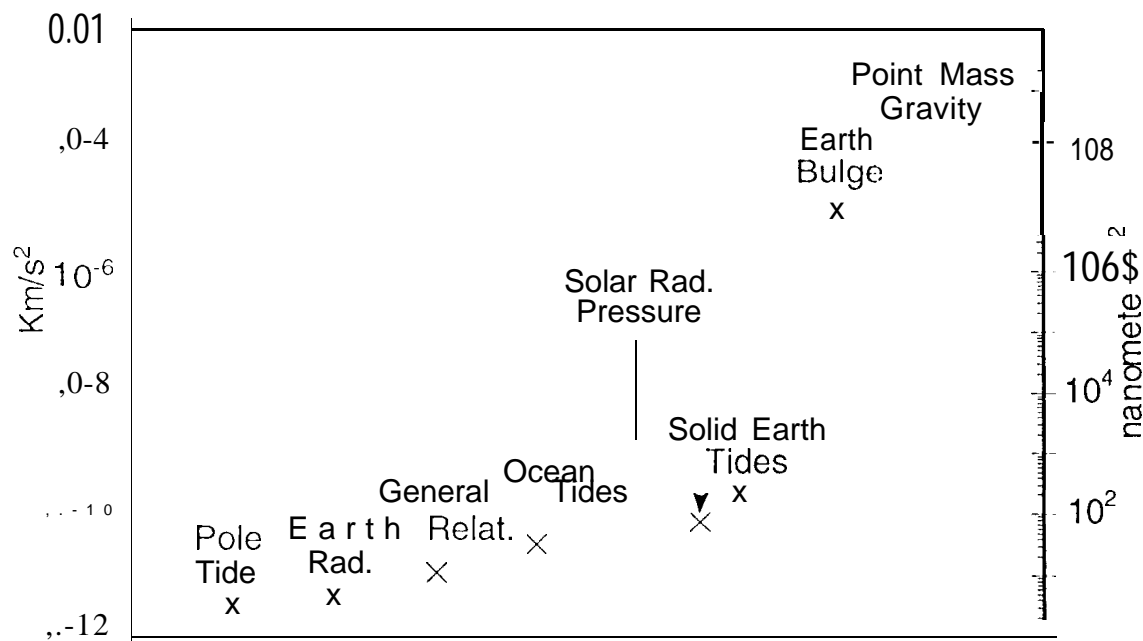


Fig. 2 Accelerations experienced by Topex/Poseidon at 1336 km altitude due to various effects modeled in GOA II.

Models

To accurately estimate spacecraft trajectories, dynamic and geometric models must be correct and complete. GOA II models in a general way the propagation of radio metric signals between transmitters and receivers. With few software constraints, generalization to many different data types is straightforward. The following data can and have been modeled and analyzed in GOA II:

carrier phase (integrated Doppler)	pseudorange
range-rate (Doppler)	1-way, 2-way, and 3-way data
GPS tracking from ground, air, sea and space platforms	GPS L1-C/A (single frequency data)
(GPS L1, L2, L5 dual frequency data (both code and code-free))	Wide Area Augmentation System (WAAS) simulations
differential GPS	satellite laser ranging (SLR)
DORIS (French Doppler tracking system)	angle data
station-satellite data	satellite-satellite data

The force models include effects which are anticipated to cause an effect down to the millimeter-level on the orbit of a low-Earth satellite, including: gravity perturbations from the sun, Earth (including ocean and pole tide perturbations), moon, and other planets; solar radiation pressure; thermal radiation from the spacecraft; drag; gas leaks; maneuvers; radiation force from the Earth (albedo); and custom-specified forces, including resonant forces. Geometric models include: Earth orientation; crustal plate motion; nutation; precession; ocean and Earth tides; ocean loading; antenna phase center offsets; coordinate system transformations (including Earth-fixed and inertial); atmospheric path delays and bending. GOA 11 also includes GPS - unique models such as the new GPS yaw control system and attitude model, and a windup model for GPS carrier phase. The observable models incorporate general relativity effects, including the needed clock models so that any station or satellite can be a transmitter and/or receiver. Fig. 2 shows relative magnitudes for some of the forces acting on Topex/Poseidon, a low-Earth orbiter at 1336 km altitude. Spacecraft-specific models are straightforward to add to the GOA 11 models and to the orbit integrator due to the modular structure of the software.

Filter/Smoother

The filter/smoother module of GOA 11 is mechanized as a (Kalman-type) square-root information filter (SRIF) with a factorized UDU smoother [2,3]. The filter/smoother has a multitude of special features which make it an extremely powerful tool for analysis of satellite tracking data, particularly GPS data. These features include:

- the capability to add process noise to any parameter;
- the capability to specify multiple different process noise models for any parameter;
- the capability to model a parameter as both a process noise and as a constant parameter in the same run to represent different components of its behavior or effects;
- the capability to vary the process noise batch interval for each process noise parameter;
- the capability to perform a full range of error assessment analyses including covariance studies, consider analysis, simulations, and the capability to perform UDU smoothing of the sensitivity matrix -- this adds a unique error analysis capability
- computation of residual sum of squares after smoothing
- the capability to remove "nuisance" white noise parameters from the run, which saves on cpu time and disk space when running the filter and smoother
- the capability to change the a priori uncertainty on bias parameters before smoothing, which saves tremendous amounts of processing when the analyst needs to test different combinations of "fixed" ground station coordinates
- the capability to model the troposphere (atmospheric) signal delays with multiple parameters, each with azimuth ranges specified

The use of factorized algorithms for both filtering and smoothing ensures numerical stability. The algorithms were developed in part at JPL and have been optimized for speed. The filter/smoother has been used for data processing from many GPS and non-GPS satellites from low-Earth to geostationary orbit. Typically JPL estimates precise GPS orbits with more than 100,000 GPS measurements/day from dozens of ground sites in an automated sequence on small UNIX workstations, with more than 25,000 parameters estimated each day. These data are used to produce the most accurate GPS orbits available, accurate to 10-30 cm. The filter/smoother itself has several layers of automated and rigorous data quality tests which identify questionable data after both the filter and smoother have finished and then automatically correct or exclude (downgrade) the questionable data one at a time. The algorithm requires a tiny fraction of the cpu time which would be normally required to rerun an entire data set with the bad measurements removed. In addition, GOA 11 can be programmed to automatically iterate several times through this process.

Output Utilities

GOA 11 is packaged with a library of output utilities to manipulate solutions in a variety of formats and reference frames. Utilities are available for handling ground station coordinates and computing baseline information and statistics; for satellite ephemeris comparisons and computations; for orbit propagation and prediction; for transformations between different reference frames, including inertial and Earth-fixed; for output of orbits in a variety of different data formats; for statistical analysis of post-fit residuals; and for calculations relating to estimates for other parameters.

Automated Processing

There are currently several automated GPS analysis procedures running daily with GOA 11 at JPL. These procedures are being used to produce near-real time precise ephemerides for Topex/Poseidon (at 1336 km altitude), which carries a GPS flight receiver, and for the GPS satellites themselves. Currently there is about a 12-hr time lag for production of 5-cm accurate (radial) orbits for Topex/Poseidon. Real-time knowledge (from orbit predictions) is maintained to about the 1 meter level.

In automated processing, GOA 11 watches JPL disks for Topex flight and GPS ground data. Ground data are fetched shortly after UTC midnight (5 pm in California) automatically through the internet, through high-speed NASA lines, through modems, or through communications satellites (Topex flight data corers through TDRS). The software calculates a geographical quality indicator, ζ , equal to the rms value over the globe of the distance from an arbitrary location on the globe to the nearest ground site. For an actual network of ground stations, ζ is computed as a double integral of the surface of the Earth. For an even distribution of stations, it would be calculated as

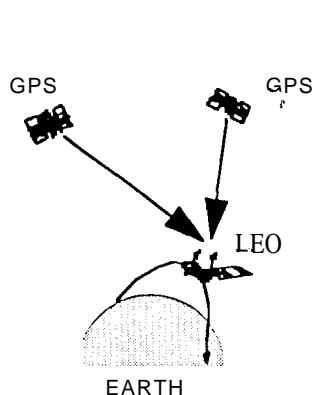
$$\zeta \approx \frac{2}{\sqrt{6}} R_e \sqrt{\pi/N} \quad (2)$$

Processing for near-real time Topex/Poseidon orbits starts automatically at $\zeta = 4000$. The automated production of GPS orbits is finished by about 10 am for data from the day before. The final GPS solutions are accurate to 10-30 cm, usually better than 20 cm. The GPS orbits are accurate to 50 cm predicted 1 day; accurate to about 150 cm predicted 2 days; and accurate to 2 meters predicted 3 days. Via FTP, the quick-look orbit products are deposited automatically on the sponsor's computers with e-mail generated from the processor (also automatically) reporting on quality indicators, orbit precisions, data residuals, and any potential problems which were noted.

USE OF GPS Y-OASIS II IN SATELLITE TRACKING APPLICATIONS

The GOA II software has been utilized over a wide spectrum of tracking and positioning applications (Figs 3a-3c). With its versatile input options and ranging capabilities, GOA 11 can determine position and velocity for fixed-location sites on the ground, or for moving vehicles in sea, land, air and space environments. Demonstrated 3D accuracies for low-Earth orbiting satellites carrying GPS receivers are 1 to 15 meters in real-time [4,5], and better than 10 cm (2 cm in the radial component) for after the fact analysis [6,7]. With the most accurate (10-30 cm) JPL/GOA II GPS orbits, any site in the world can be positioned to about 1 cm [8,9]. GOA II simulations recently explored strategies for Wide Area Augmentation System operation, which will provide real-time location information to all commercial airliners in several years. JPL has also developed an innovative new technique called GPS-like tracking [10], which enables orbit determination for satellites at virtually all altitudes, even when the satellites do not carry GPS receivers. GPS-like tracking uses GPS measurements to calibrate error sources in the non-GPS tracking data. Since GOA II models conventional (non-GPS) tracking observable, it can be used to analyze real or simulated data from many existing or future satellites which use non-GPS tracking systems. The performance of such systems depends on many factors, but a recent analysis of Doppler data with

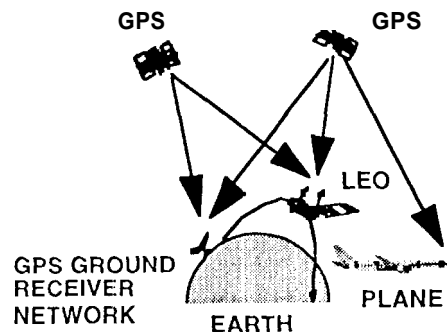
GOA 11 from several low-Earth orbiters showed that sub-decimeter level accuracy can be achieved with laser ranging (SLR) or a French Doppler tracking system (DORIS) [11].



Direct GPS Tracking

- Real time
- Military
- Commercial
- Real-time accuracy:
 - 1 to 15 m for LEO

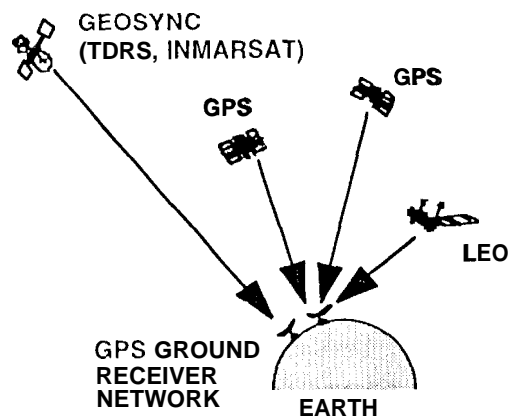
Fig. 3 (a)



Differential GPS Tracking

- Geodesy, oceanography
- Commercial
- Military
- GPS orbit accuracy: 10-20 cm
- LEO orbit accuracy: < 10 cm
- Ground coordinate accuracy: 1 cm
- Aircraft applications

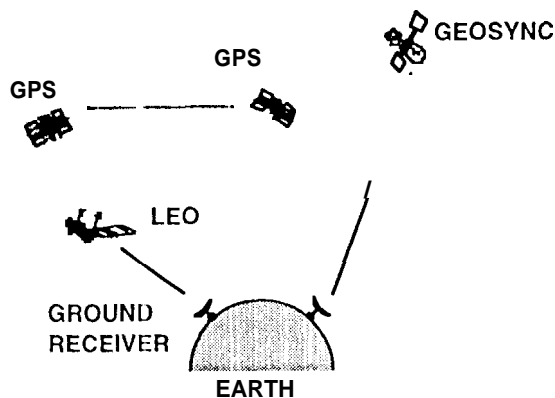
Fig. 3 (b)



GPS-like Tracking

- Real time
- NASA
- Military
- Commercial
- TDRS orbit accuracy: 20 m
- Potential m-level accuracy GEO
- LEO demo planned 1996

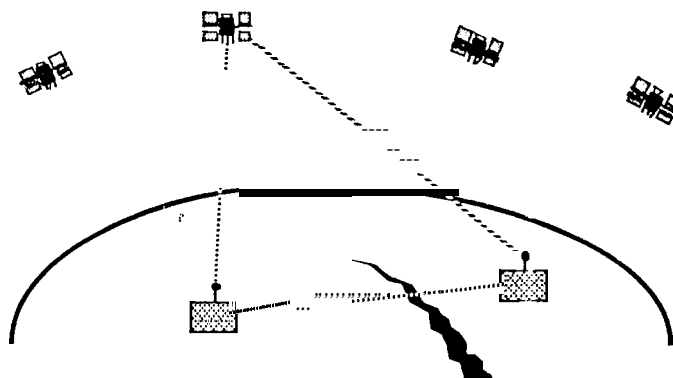
Fig. 3 (c)



Other data types

- General spacecraft-spacecraft observable
- 1-way, 2-way, 3-way doppler, range, phase
- Angle measurements

Fig. 3 (d)



Sub-cm geodetic measurements

- Continuous monitoring, more than 100 global sites
- Rapid response to earthquakes
- Unequaled accuracy (millimeters)

Fig. 3 (e)

Fig. 3. GIPSY-OASIS 11 has been used or demonstrated for use at JPL in a wide variety of satellite tracking applications. (a) Real-time positioning of low-Earth orbiters; (b) High-precision differential GPS positioning for ground, air, and space users equipped with GPS receivers; (c) GPS-like tracking of satellites in low-Earth to geosynchronous (and higher) altitudes; (d) general (non-GPS) spacecraft tracking in low- to high-Earth orbit; and (e) precise ground geodesy, seismic monitoring arrays, and surveying.

Several hundred users worldwide employ GOA 11 for precise geodetic and surveying applications. In its highest precision mode, GOA 11 can provide several-mm precision measurement of relative ground station locations [8,9]. In the U.S. and Japan, GOA 11 is being used in a system to monitor hundreds of ground sites for crustal movement related to seismic activity.

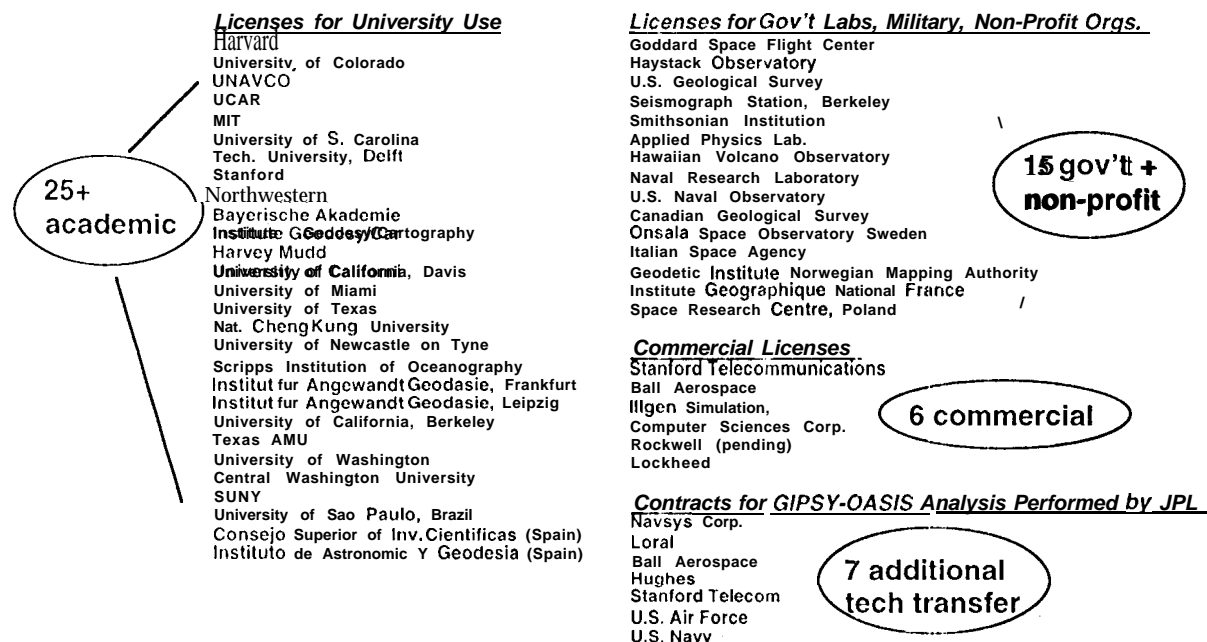


Fig. 4 Licensed users of GOA II. Also shown are organizations contracting work with JPL for analysis of satellite tracking with GOA II,

GOA11 has extensive error evaluation capabilities, including a unique consider analysis tool [2,3] which allows for smoothing of sensitivities, and a multipath simulator. With these tools, tracking system design and trade-off studies can be carried out. Such tools, in fact, were used in the late 1980s to design the precise GPS global tracking system which JPL is currently using for precise orbit determination. More recently, these error evaluation tools have been used in the commercial sector, by the U.S. Air Force, and by the U.S. Navy, under contract to JPL.

Fig. 4 lists current licensed users of GOA 11. It includes non-commercial, government, non-profit, and commercial users. The software is licensed through the California Institute of Technology. Information about licensing, arrangements can be obtained from the first author of this paper.

ACKNOWLEDGMENTS

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